The NPOI: Description and Design Considerations

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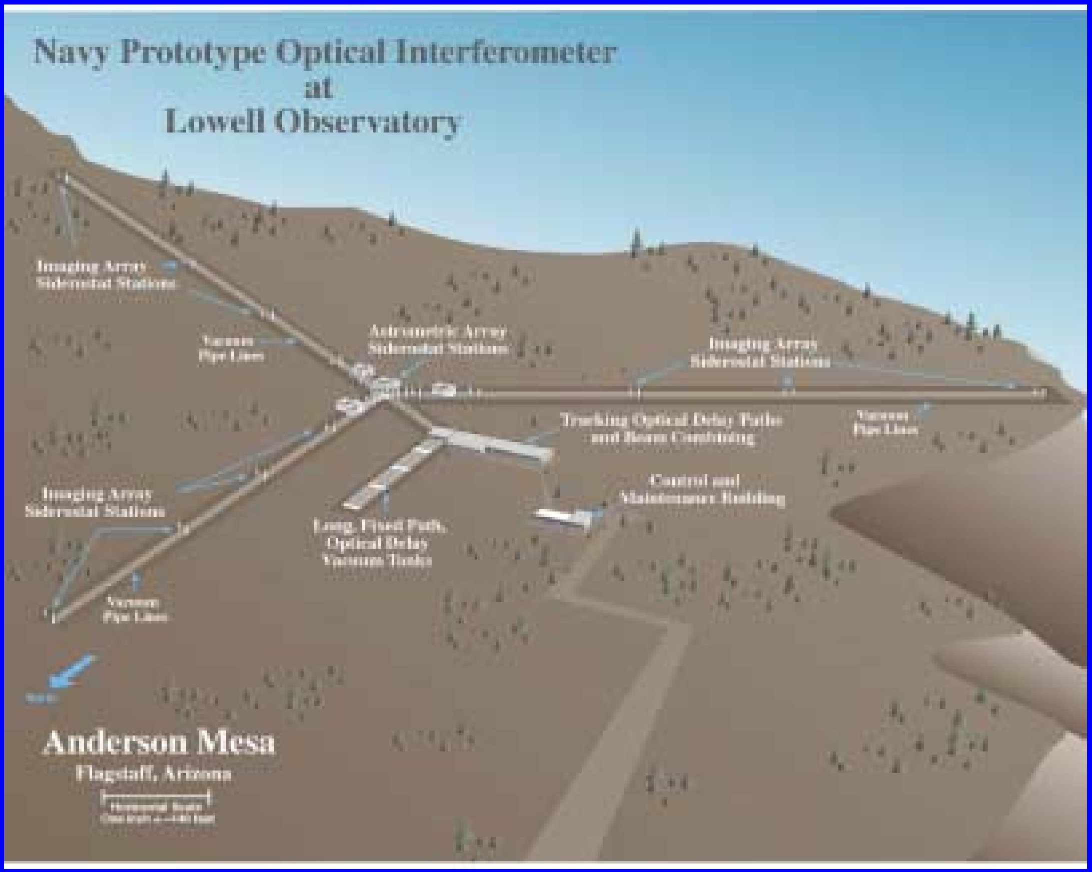
Purpose of Talk

- Provide a Description of the NPOI
- Show how the general ideas presented earlier this week influence the design of an actual instrument.
- Give an Introduction to data reduction procedures which will be needed later today.

NPOI Site



Navy Prototype Optical Interferometer
at
Lowell Observatory
Imaging Array Siderostat Stations
Vacuum Pipe Lines
Astrometric Array Siderostat Stations
Imaging Array Siderostat Stations
Tracking Optical Delay Paths and Beam Combining
Vacuum Pipe Lines
Control and Maintenance Building
Imaging Array Siderostat Stations
Long, Fixed Path, Optical Delay Vacuum Tanks
Vacuum Pipe Lines
Anderson Mesa
Flagstaff, Arizona
Horizontal Scale

NPOI

NPOI view

Components of an Interferometer

1. Array Stations – Aperture, Geometry
2. Angle Tracking – FSM, Sensors
3. Beam Transport – Vacuum, Geometry

   Dispersion, Polarization and Beam Rotation
4. Delay Compensation – Course and Fine
5. Beam Combination
6. Fringe Detection

I. Array Elements

- NPOI uses Siderostats (Flat Primary)
- Great for Astrometry
  - Mark III Heritage
  - Metrology System
- Reasonable for Small Apertures
  - Feed Direction Elevated 20 Degrees to give better Sky Coverage.

Telescope

Array Geometry

- 6 Elements in a Partially Redundant Y
  - 3 Elements on Each of Three Arms
    - Two arms at a time.
  - Reconfigures with Multiplier of 1.7
  - 10 Stations per Arm.
- Longest Baseline 435 meters
  - Resolution ~ 1 nanoRadian = 0.2 mas

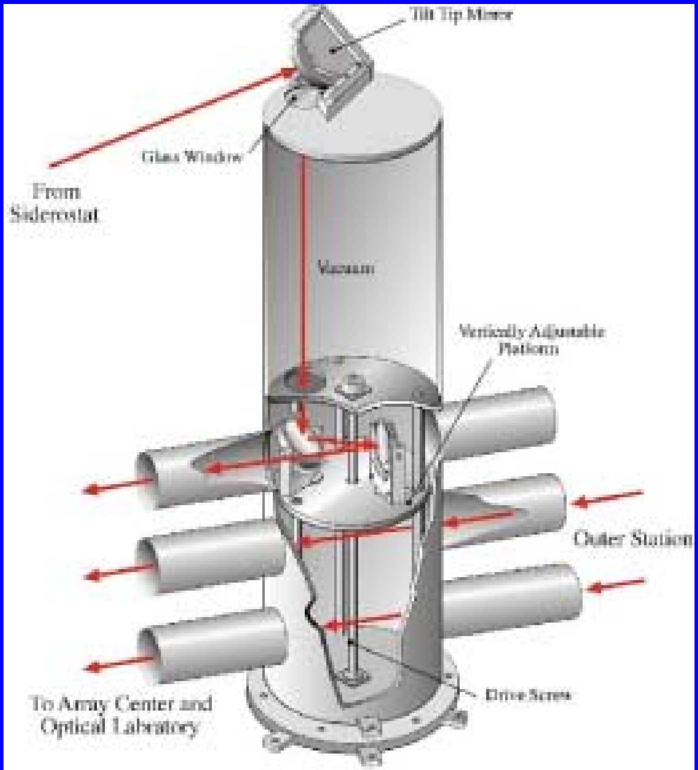
II. Angle Tracking

- The NPOI Includes no Pupil Management
  - On Axis Design → No Problem
- Angle Tracking Errors Translate into Beam Shear
- Fast Steering Mirror Located at Telescope
  - Shear θ L = 3.5 mm
    - One Arc Second
    - 700 Meters
- Angle Sensing at Back end (discussed later)

Angle Tracker

Array Station

North Arm



Entrance to Vacuum Light Path
for
North and Southwest Arms

III – Beam Transport

- Even though the Feed System Looks Easy, there are a Number of Design Considerations.
  - Differential Refraction
  - Diffraction
    - Set Beam Diameter through Feed System
  - Dispersion
  - Beam Rotation
  - Polarization Effects

Dispersion

- Through most media, the optical path length depends on wavelength
- If the arms of the interferometer are not matched, different wavelengths will interfere at different delays and the visibility of a broadband channel will be reduced.

Group Delay

- If we replace some of the optical path with a dispersive material,

$$\varphi = \frac{2\pi[d_V + (n-1)d_A]}{\lambda} = \frac{2\pi[d_V + (n_0 + n_1\lambda + f_\lambda)d_A]}{\lambda}$$

$$= \frac{2\pi[d_V + n_0 d_A]}{\lambda} + n_1 d_A + f_\lambda d_A / \lambda$$

- The constant and linear portions of the index of refraction shift the fringe and fringe packet but do not impact the observed visibility amplitudes.

Dispersion Compensation

- Adding Glass to the Optical Path can Compensate Reasonably well for the Air Mismatch Between Arms

- We Chose to Keep the Entire Optical Path in Vacuum.

Internal Seeing

- Even if you (mistakenly?) think you can handle the dispersion, the Feed system should be in vacuum to prevent seeing problems with long near ground optical paths. Especially Important for
  - Long Path lengths
  - Large beam diameters

NPOI Vacuum Seals

- Very low cost
- Maintenance is an issue, but not severe

- Mechanical design is MUCH more subtle than it appears

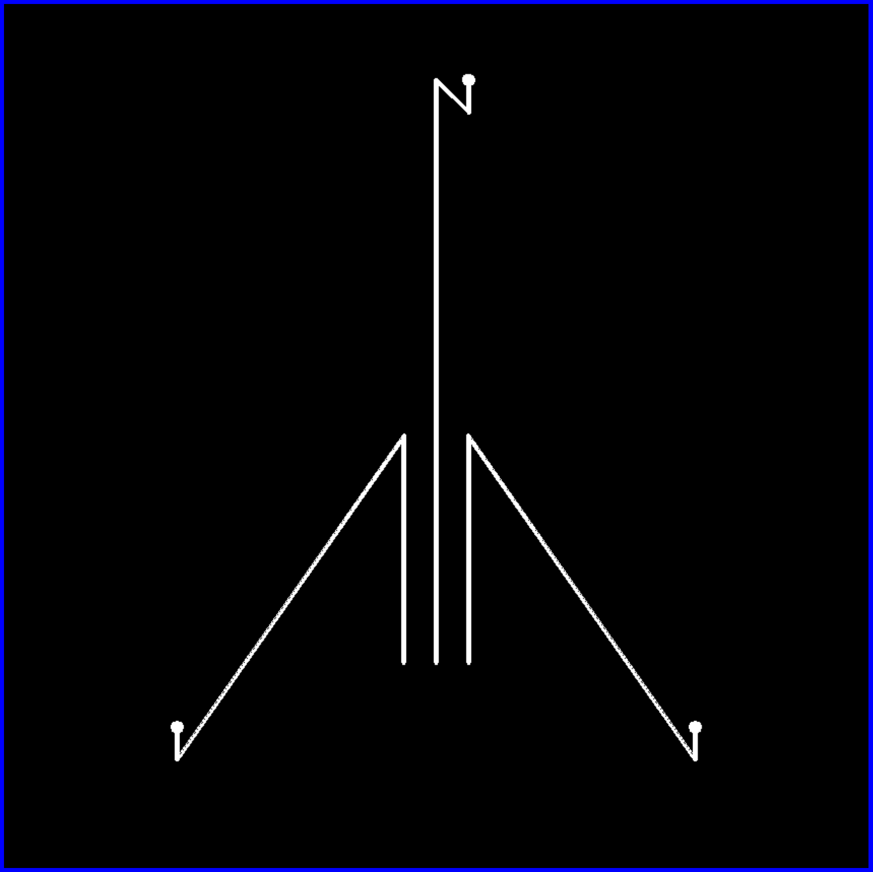
Feed System Pipes

West Arm

Beam Rotation and Retardation

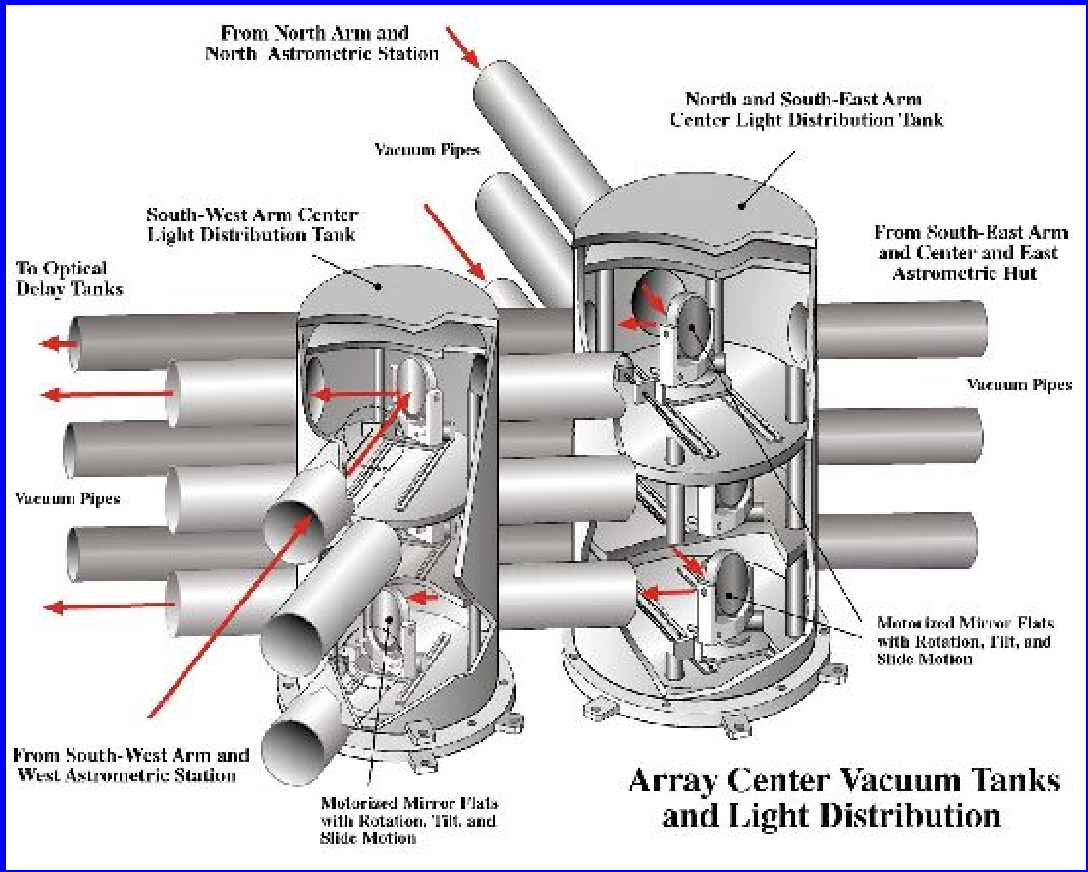
- Visibility Loss can occur from Field Rotation and polarization mismatch between the arms of the interferometer
- Easiest Solution
  - Make all arms identical
  - And in plane rotations commute

Optical Layout



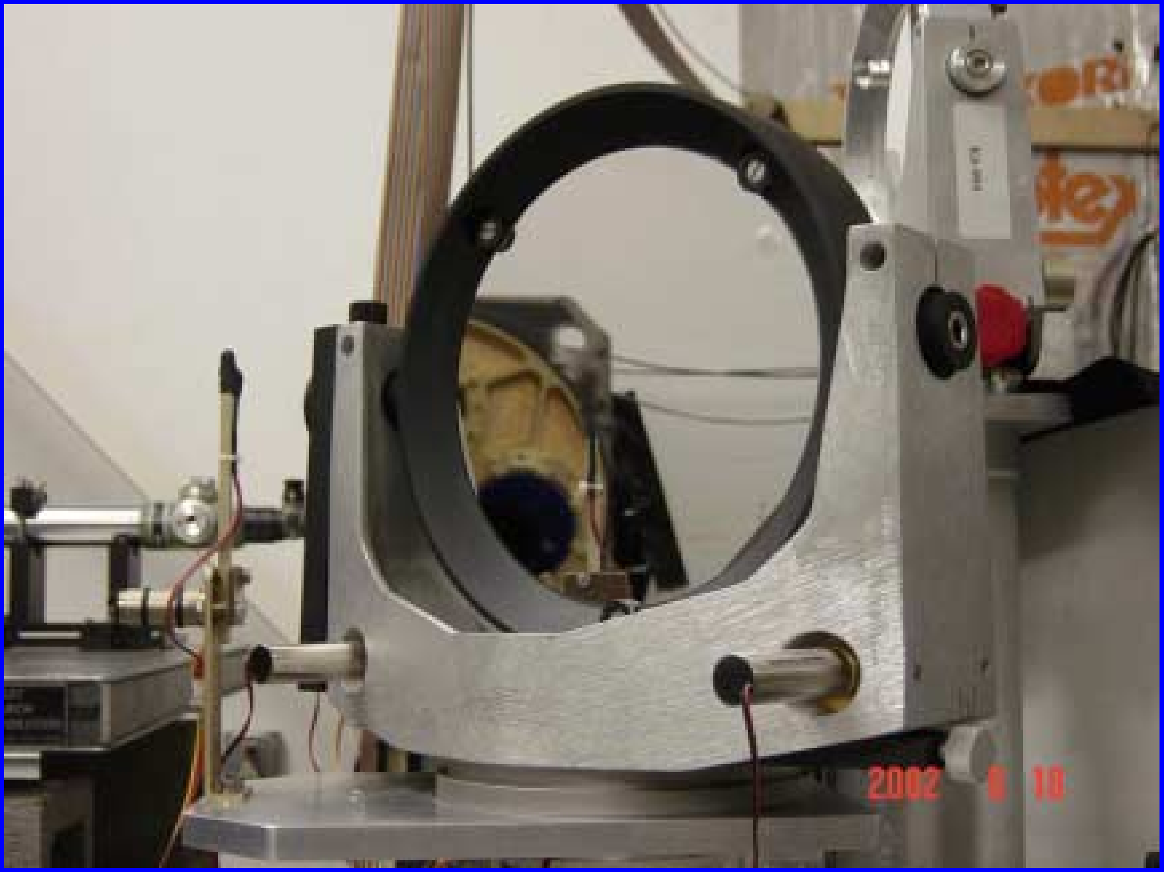
Array Center

Array Center Details



Array Center Vacuum Tanks
and Light Distribution

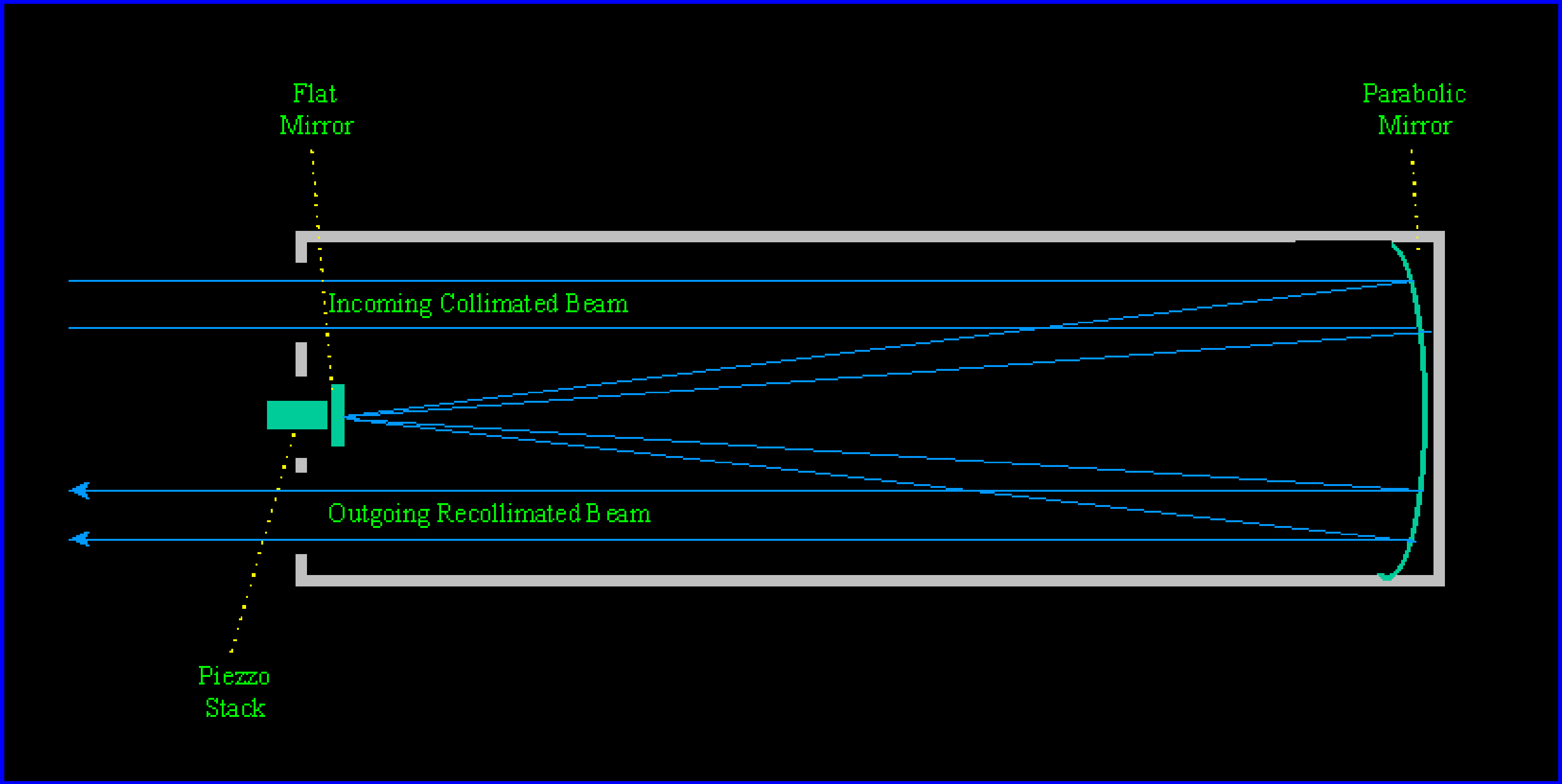
All Mirror Mounts Are Automated



IV – Delay Compensation

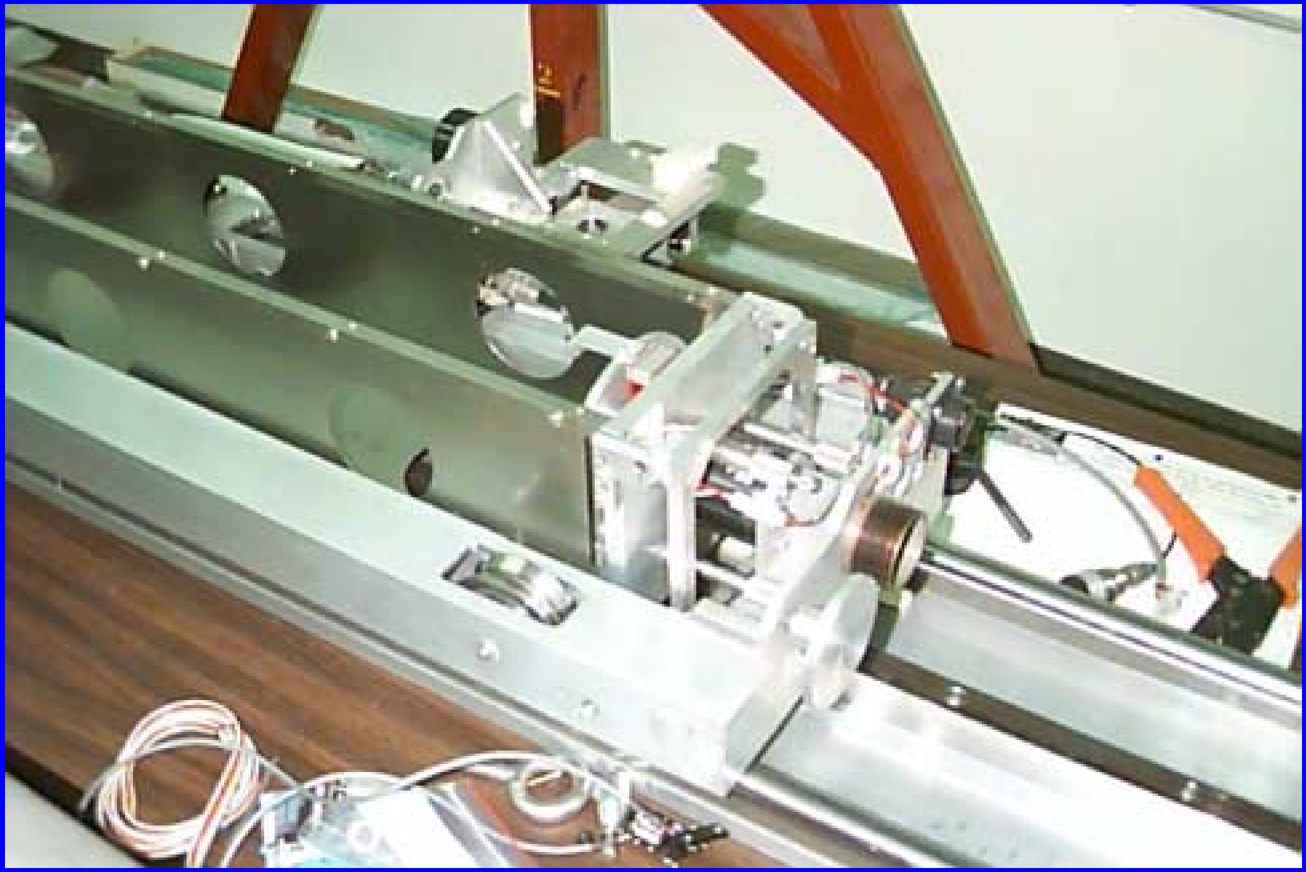
- Divided into two parts
  - FDL – Fast delay lines – Fringe tracking
    - Retroreflector design for Continuous motion
    - Maximum Delay – 35 meters
    - 30 minutes fringe tracking on 500 m baseline
    - 2 cm/sec with 10 nm rms
  - LDL – Long delay lines
    - Flat Mirrors – Delay added in 30 meter segments
    - Maximum Delay – 480 meters

FDL cart



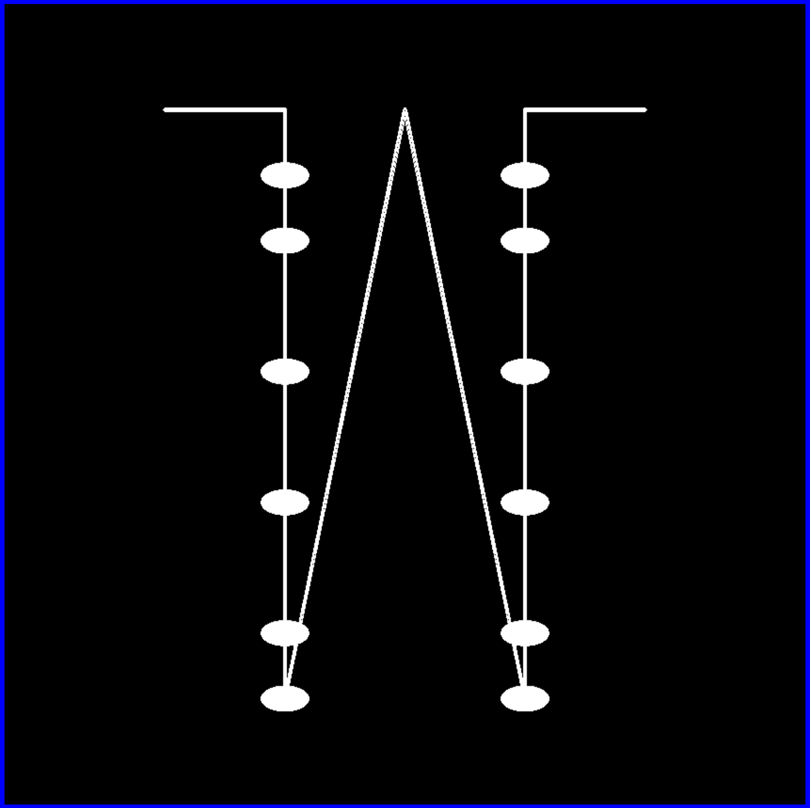
Flat Mirror
Parabolic Mirror
Incoming Collimated Beam
Outgoing Recollimated Beam
Piezzo Stack

Optics Carts



FDL Assembly

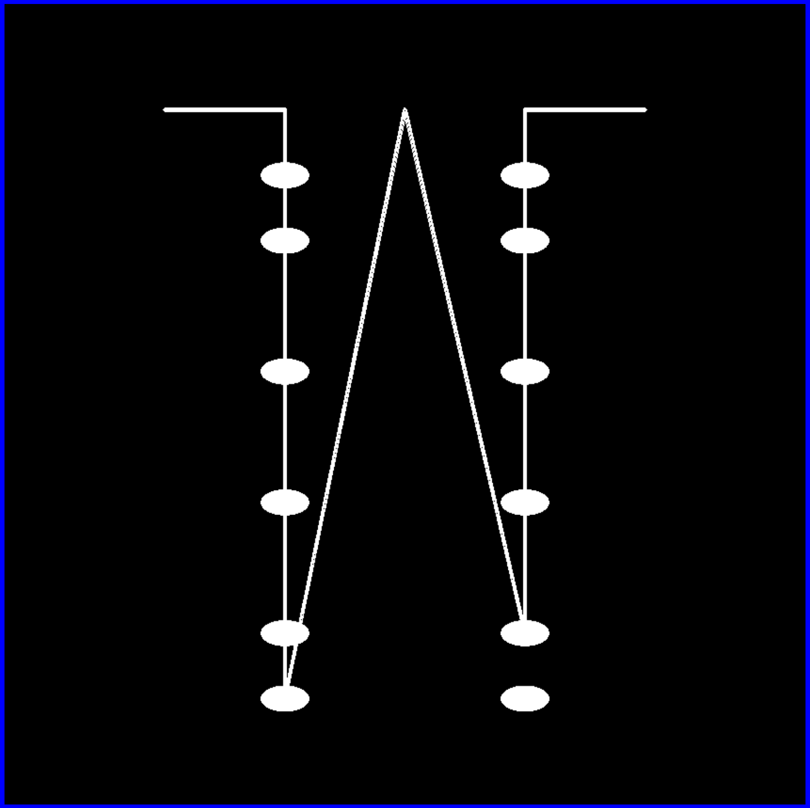
LDL Geometry



Stn	Dist.	Meters
1	0	0
2	1	30
3	3	90
4	5	150
5	7	210
6	8	240

Stn 6+6 = 480 meters

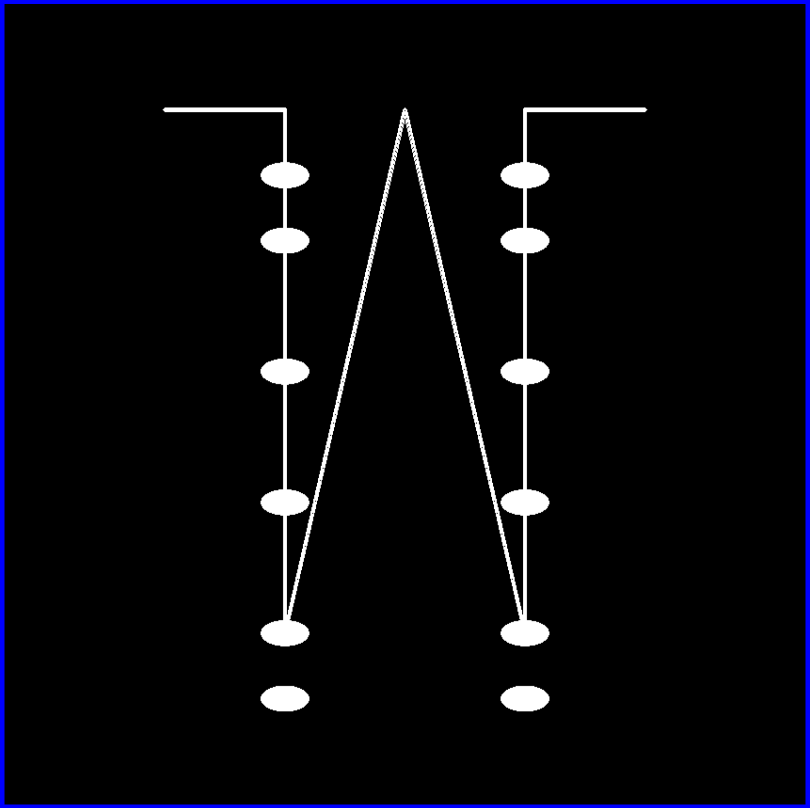
LDL Geometry



Stn	Dist.	Meters
1	0	0
2	1	30
3	3	90
4	5	150
5	7	210
6	8	240

Stn 6+5 = 450 meters

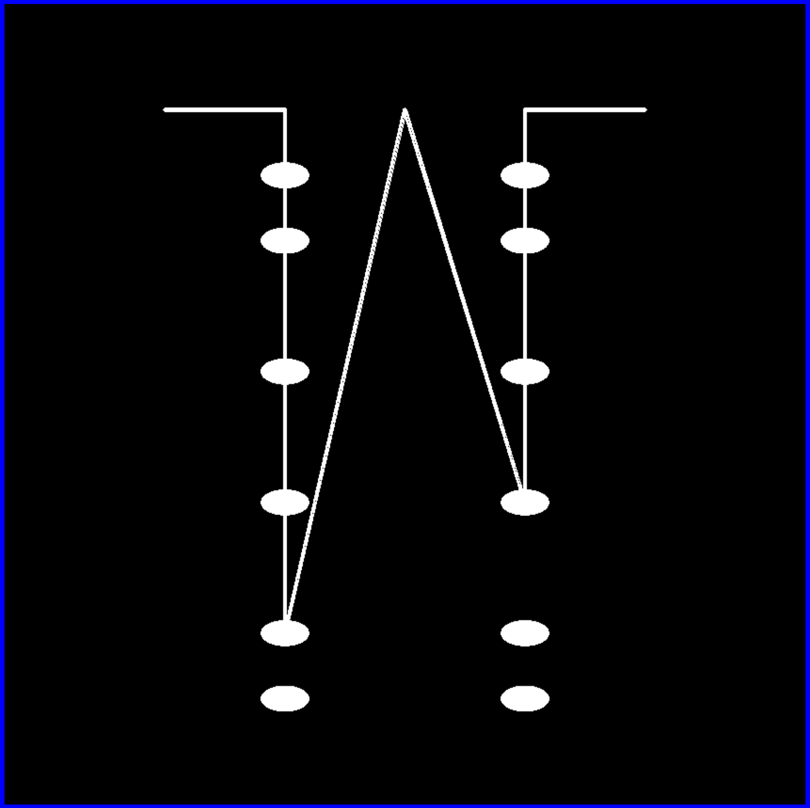
LDL Geometry



Stn	Dist.	Meters
1	0	0
2	1	30
3	3	90
4	5	150
5	7	210
6	8	240

Stn 5+5 = 420 meters

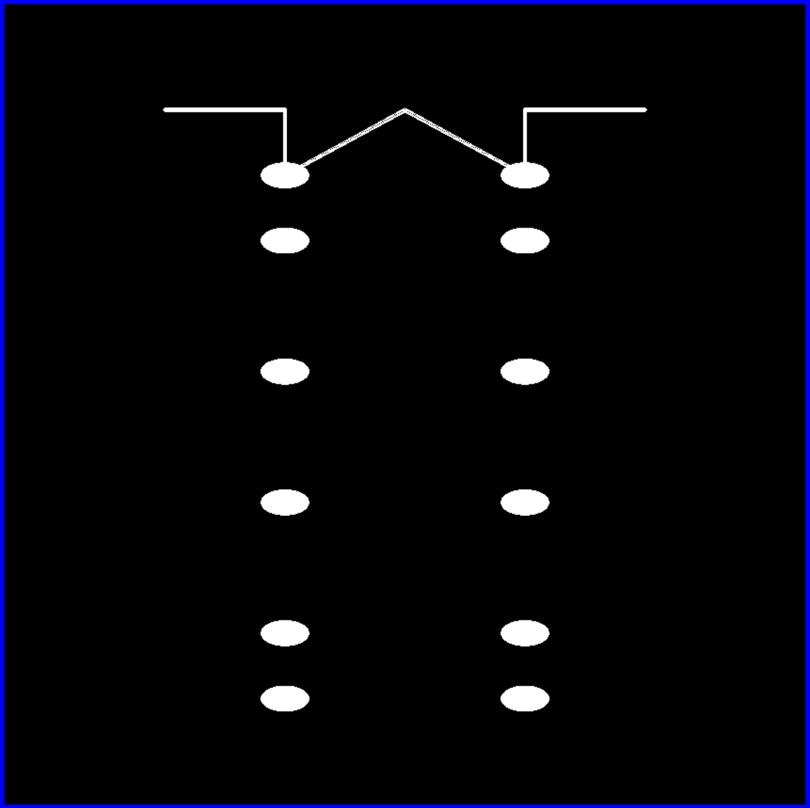
LDL Geometry



Stn	Dist.	Meters
1	0	0
2	1	30
3	3	90
4	5	150
5	7	210
6	8	240

Stn 5+4 = 360 meters

LDL Geometry



Stn	Dist.	Meters
1	0	0
2	1	30
3	3	90
4	5	150
5	7	210
6	8	240

Stn 0+0= 0 meters

LDL Starlight view

LDL Station Details

LDL

LDL Pipes

Bridge

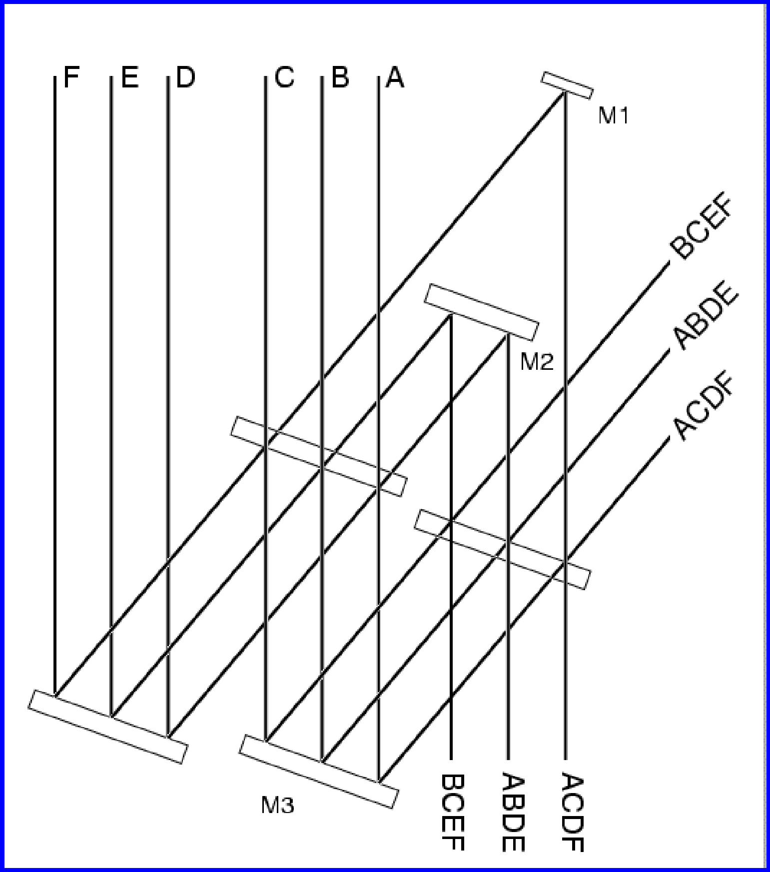
NPOI Long Delay Lines

- The NPOI LDLs violate the symmetry rule.
  - The middle mirror is above the plane of the other mirrors
  - Worst case beam rotation 0.5 degrees
  - Visibility loss $< 0.1\%$

V – Beam Combination

- 3, 4-on-one Combiners run in Parallel
- Unpleasant Trade Between
  - Too long a Modulation
  - Too many Detectors

Beam Combiner Schematic



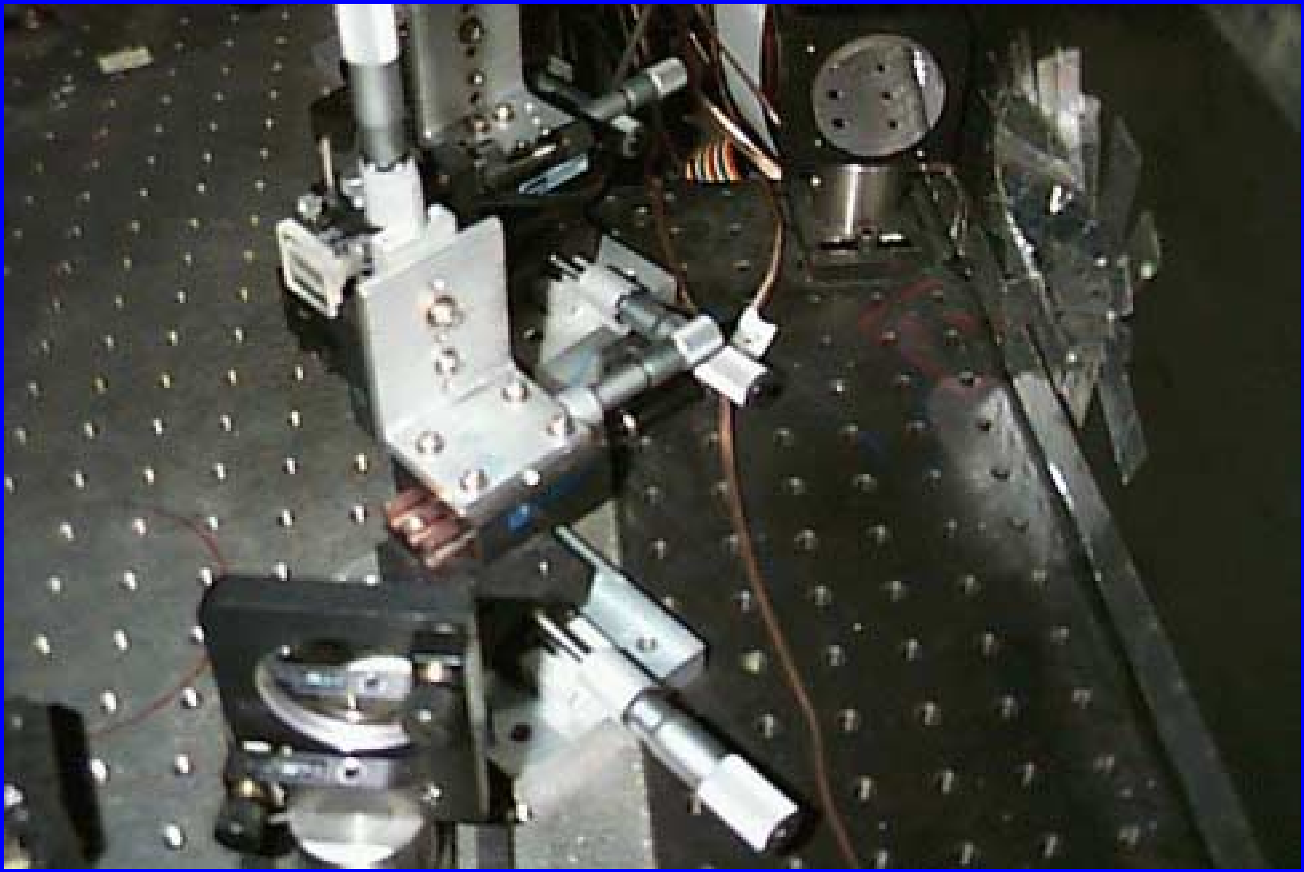
Beam Combiner Implementation

Fringe Analysis

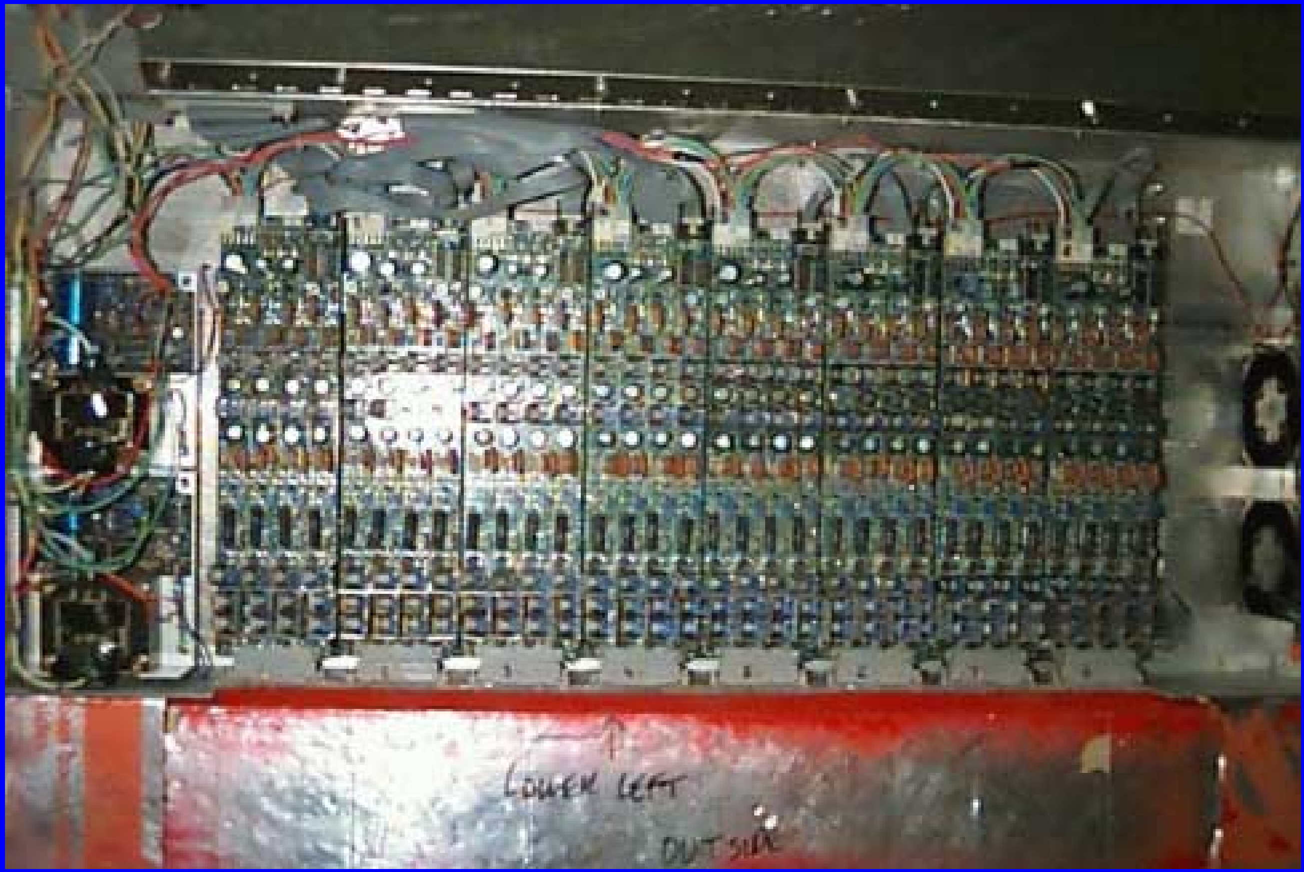
- Wide Bandpass is needed
  - Sensitivity
- Narrow Bandpass is needed
  - Long Coherence time
  - Science
- Solution – Spectrograph in combined beam
- Detectors – Photon counting array of APDs
  - Built with lenslet array and single detectors

Fringe Analysis Spectrograph

Lenslet Array



APD Array



Angle Sensing

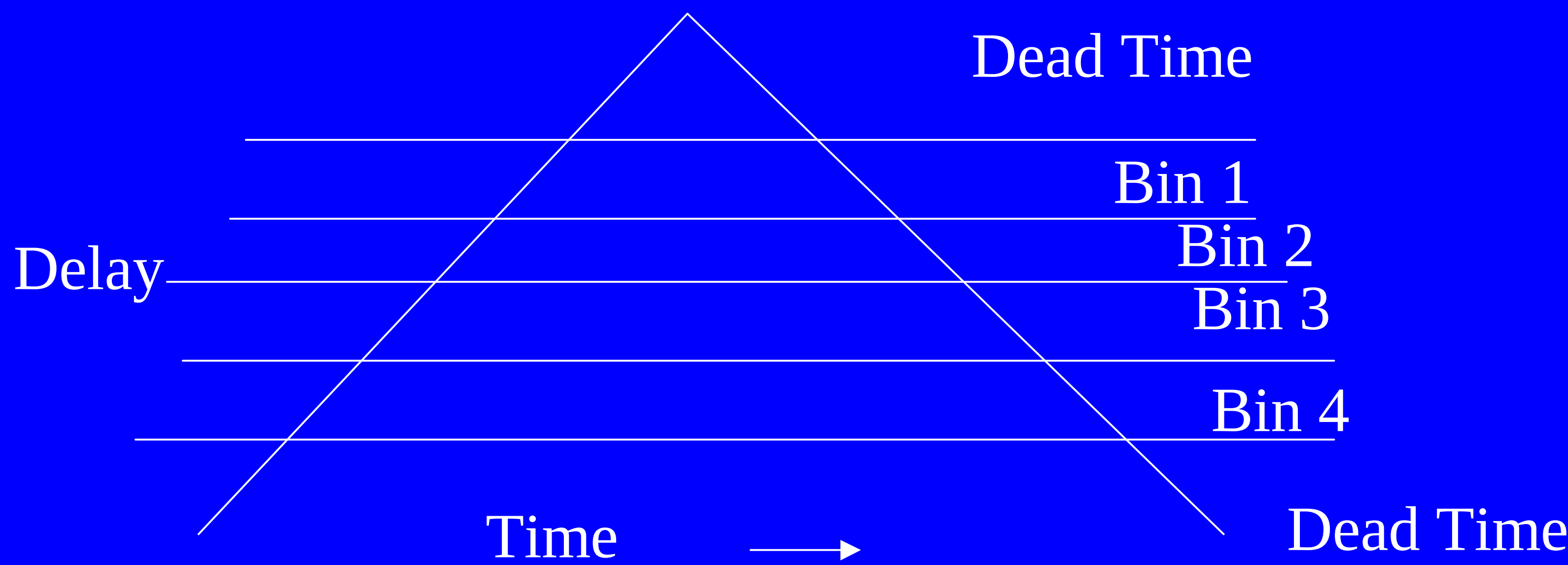
- Located in Beam Combiner with actuator at Telescope
- Implementation
  - Photon Counting Quad Cell
  - 2x2 Lenslet array feeds fibers feeds APDs
  - Central hole in Quad improves sensitivity
  - Error signal is in units of image diameter

Angle Tracker

Fringe Detection

- We use a temporal fringe modulation
  - Modulation occurs in FDL
- Delay Varies with time
- Photons are detected synchronously with modulation
- Data is binned into increments of similar delay called Bins

Fringe Modulation Details

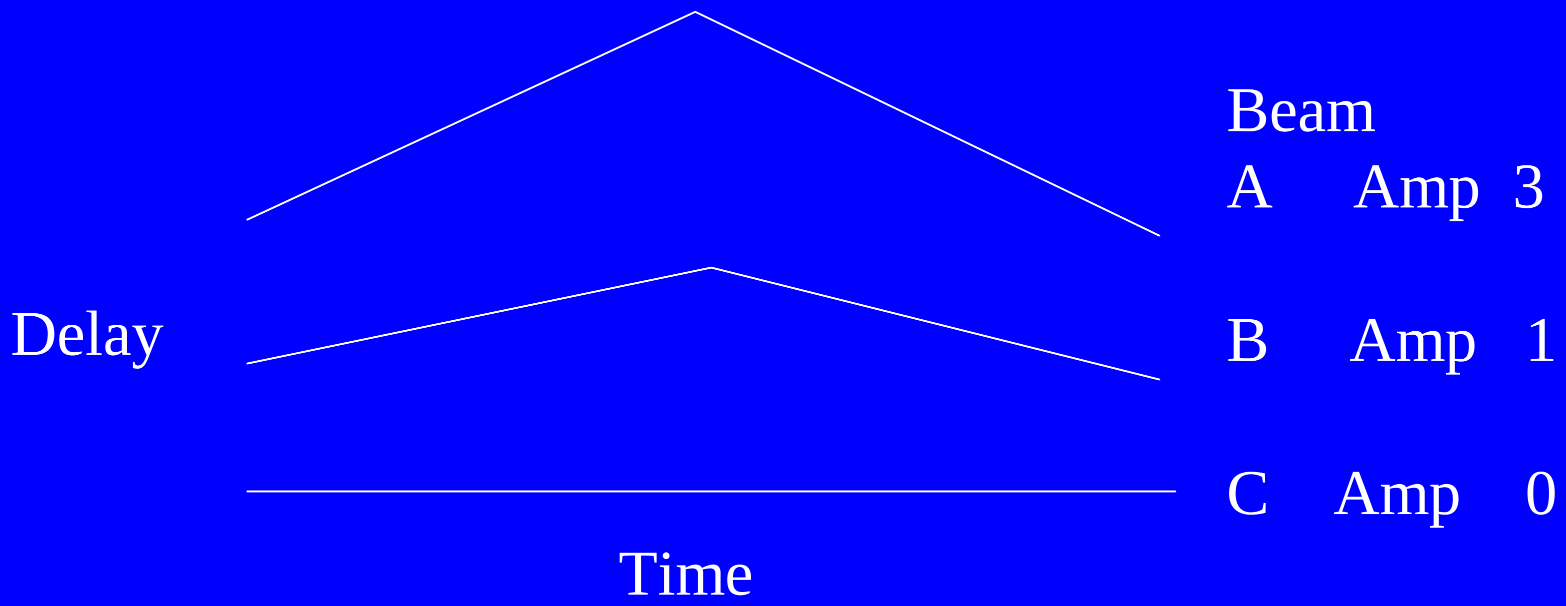


The modulation is a even number of wavelengths at all wavelengths.
Dead Time varies with Wavelength

Multiple Baseline Demodulation

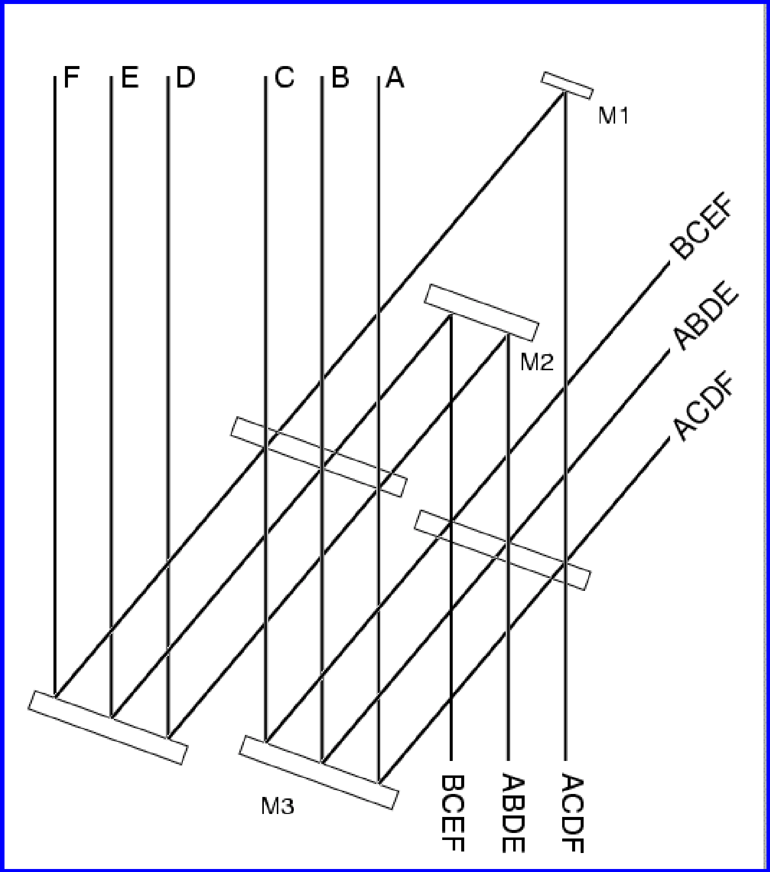
- Each Telescope has a different Modulation Amplitude
- The Difference in Modulation Amplitude between two Beams gives the fringe frequency on that baseline
- No two Baselines on the same Detector have the same Fringe Frequency.

Fringe Detection



Baseline	A-C	A-B	B-C
Fringe Frequency	3	2	1

Modulation Scheme

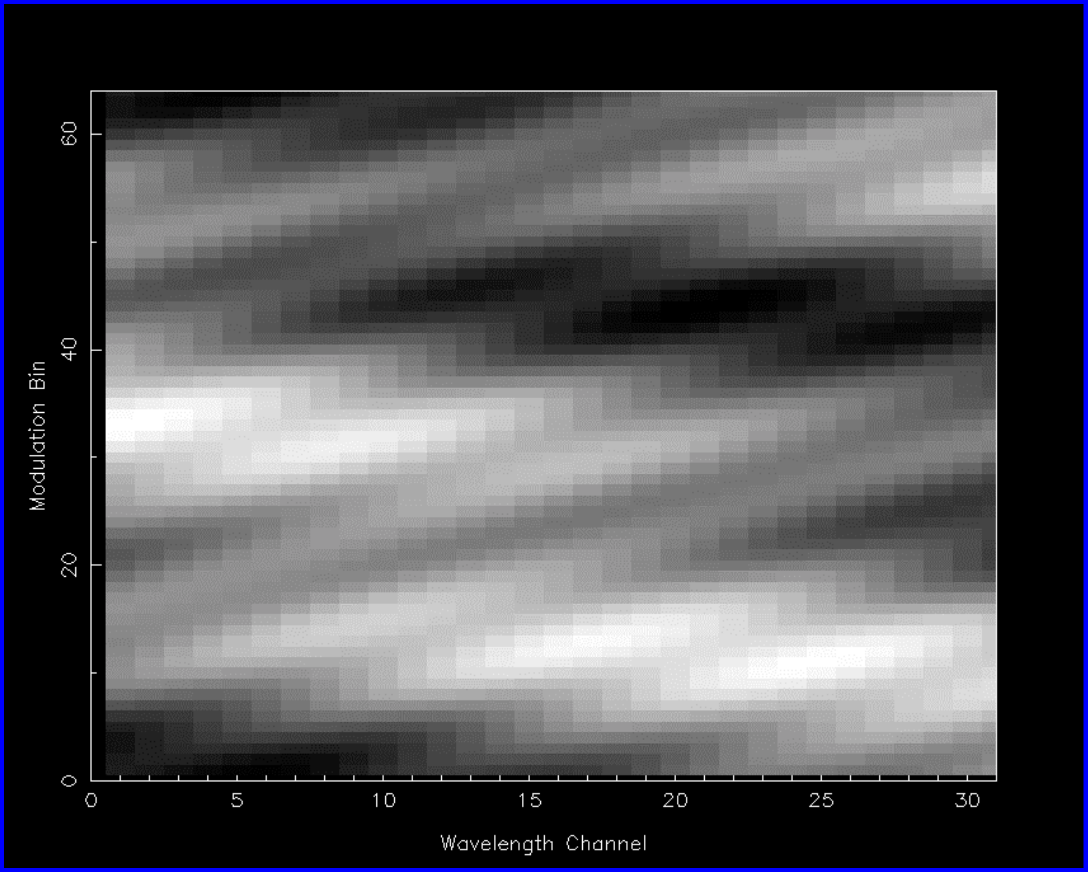


- Modulation
  - A B C D E F
  - 0 2 1 5 6 8
- A-C-D-F
  - 1, 5, 8, 4, 7, 3
- A-B-D-E
  - 2, 5, 6, 3, 4, 1
- B-C-E-F
  - 1, 4, 6, 5, 7, 2

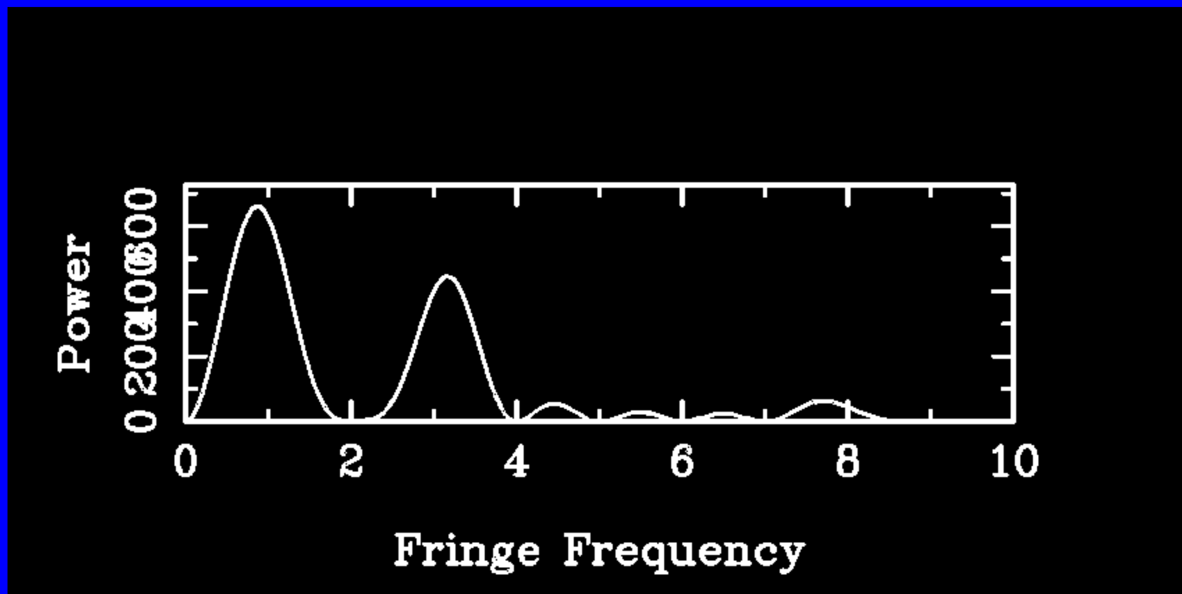
VI – Fringe Analysis

- Data are a Data Cube:
  - Intensity versus Wavelength and bin
  - 64 Bins evenly Sample k Wavelengths
- The Signals – Sine Waves buried in Noise
- The Goal is Simple, Unbiased estimate of the Amplitude and Phase of Each Signal.

Data frame



Fringe Spectra



- Fourier Transform of Bin Counts
- Amplitude and Phase at a Frequency Corresponding to the Fringe Frequency of a Baseline is the Complex Visibility for that baseline

Calibration, Bias and Crosstalk

- Definitions
  - Calibration. A Multiplicative Factor Affecting the Visibility Amplitude $V^2 = \eta\gamma^2$
  - Bias. And Additive factor affecting the Visibility Amplitude $V^2 = \gamma^2 + \beta$
  - Crosstalk. The Visibility Amplitude for one Baseline Depends on the Measured Amplitudes for the other Baselines. $V_k^2 = \gamma_k^2 + \sum_{j \neq k} \kappa V_j^2$

Calibration

- Calibration Should be Performed Separately for Each affect that Reduces the Fringe Contrast.

Calibration

- Calibration Should be Performed Separately for Each affect that Reduces the Fringe Contrast.
- This is not Done.
- Because Calibrations are Multiplicative, it is possible to lump them together and do a Single Calibration off a Nearby Star.

Example: Photometric Calibration

$$I = \sum_i I_i \left(1 + 2\sum_{k,l} \frac{\sqrt{I_k I_l}}{\sum_i I_i} \gamma_{k,l} COS(\tfrac{2\pi d}{\lambda} + \phi_{k,l}) \right)$$

- Relative Brightness of Stars Enters Linearly when more than two Beams are present
  - Quadratic for Pair-wise

Bias

- The Only Bias Term in Optical Interferometry is due to detector Statistics

Fringe Detector Statistics: Bias

- Squared Visibility is the value of the Fringe Power Spectrum at the Fringe Frequency
  - Value always > 0
  - V^2 biased by the Detector Statistics

$$V^2 = 4\frac{\left\langle X^2 + Y^2 \right\rangle - \left\langle \sigma^2(I) \right\rangle}{\left\langle I \right\rangle^2}$$

- intrinsically a correlation measurement
  - Depends on the Second Moment of Detector Statistics

Fringe Detector Statistics: Crosstalk

- For Photon noise Bias correction is Easy.
- Non-Photon noise is a problem
  - Needs Lots of Data to Characterize
- Dead time like corrections
  - Variance is quadratic in count rate
  - Causes Cross-talk

Crosstalk from Detector Statistics

- When More than One Baseline is on the Same Detector and the Detector Statistics are non-Linear, there is inherent Cross talk between the Baselines

$$V_j^2 = 4\frac{\left\langle X^2 + Y^2 \right\rangle - \sigma^2(\left\langle I \right\rangle)}{\left\langle I \right\rangle^2} - \mu \sum_i V_i^j$$

$$\sigma^2(I) = \alpha + \beta I + \mu\sigma^2$$

Crosstalk

- Everything causes crosstalk
  - Detector Statistics
  - Atmospheric Fringe Motion
  - Non-linear detectors

The Control Room

Atmospheric Fringe Motion

- Atmospheric Turbulence Causes an Error in Fringe Frequency
  - t0 is the time it takes a fringe to move 1 radian

$$\Delta V = V_{atm} = \lambda / 2\pi t_0$$

$$V_{\mathrm{mod}} = k\lambda / t_{\mathrm{mod}}$$

$$\frac{\Delta f}{f} = \frac{\Delta V}{V} = \frac{t_{\mathrm{mod}}}{2\pi t_0 k}$$